

# SMALL PUNCH TESTING OF ADVANCED METAL MATRIX COMPOSITES

A dissertation submitted in fulfilment  
of the requirements for  
the degree of  
Doctor of Philosophy

By

Jonathan Chung Kit Mak

BSc (Honours) in Nanotechnology

Department of Physics and Advanced Materials

Faculty of Science

University of Technology, Sydney

June, 2011



For my loving parents  
Mak Shu Kai and Mak Cheuk Ping

*I know that the molecules in my body are traceable, to phenomenon in the cosmos, and it's out of 15 pounds of grey-matter that figured this out! The kingship with the cosmos that resonates deeply with new age thinking... But I'm not apologetic about that, it's what we find, if whatever we find resonates with whomever. Go ahead take it!*

*I want somebody to put electrodes on my head, and when I reflect on, our kingship with the cosmos, when I do the calculations that shows, that a 15 tonne meteorite that we have in the Rose Centre for Earth and Space, it's an iron meteorite, when I do the calculations that shows, that if you take all the iron from the haemoglobin of the people in Tri-State Area of New York City. You can recover that much iron out of their blood and realise that the iron from that meteorite and iron from your blood has*

*Common origin! In the core of a star!*

*Tell me what part of my brain is lighting up because that excites me. That makes me want to grab people in the street and say "have you heard this"??*

*It's quite literally true that we are stardust... In the highest exalted way that one can use that phrase.*

*When it was announced that we were going to cancel the Hubble Telescope the greatest outcry to not do that was not the Astrophysicist, it wasn't from within NASA, it was the public. It was all over the op-ed pages and the talk shows. The public took ownership of the Hubble Space Telescope because the Universe was coming into their bedroom, into their living room and onto their computer. They were participants on the frontiers of discovery. And as far as I can tell, if you let them know, that we're not just something in the Universe, but in fact, given the Chemistry of it all and the Nuclear Physics of it all. Not only are we in the Universe, the Universe is in us...*

*And, I don't know, any deeper spiritual feeling, than what that brings upon me.*

*Neil deGrasse Tyson  
Beyond Belief Conference, 2006*

## ABSTRACT

---

This Doctoral thesis investigates the use of the small punch test (SPT) as a means for assessing yield strength and fracture toughness from alloys and metal matrix composites (MMCs). Metal matrix composites have been implemented in many high performance applications due to their high strength to weight ratio, however, low fracture toughness and ductility remain a concern for these materials. Therefore, techniques for conventional mechanical tests including tensile and fracture toughness tests have been utilised to assess the mechanical performance for these materials, however, more often than not, situations will arise where there are limited volumes of material for testing, this is especially true in the case of MMCs. Thus, there is great demand for mechanical tests that are capable of assessing small samples. The small punch test (SPT) is proposed as a suitable small specimen mechanical test technique that is capable to meet this challenge. This research examines the SPT on MMCs and the effect of ceramic reinforcement content on yield strength and fracture toughness. To achieve this small punch, tensile and fracture toughness tests are performed on as-received 7A04-T6 aluminium and TC4 titanium alloy and related MMCs. In particular, small punch values such as the small punch elastic-plastic load,  $P_y$ , equivalent fracture strain,  $\epsilon_{qF}$ , and small punch energy,  $E_{SP}$ , are correlated against conventional tensile yield strength,  $\sigma_{YS}$ , and plane-strain fracture toughness,  $J_{Ic}$ , values. Furthermore, empirical, analytical and numerical solutions are assessed. A polynomial relationship is found to correspond well with  $J_{Ic}$ - $\epsilon_{qF}$  relationship for both elastic and elastic-plastic materials. This research further investigates and develops the application of the SPT which may lead to an inexpensive straightforward multi-mechanical non-destructive test technique for advanced alloys and MMCs.

## CERTIFICATE OF AUTHORSHIP

---

I certify that the work on this thesis has not previously been submitted for a degree nor has it been submitted in part of the requirements for a degree except when fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are acknowledged within this thesis.

Candidature's Signature

---

Dated: 30-June-2011

## ACKNOWLEDGEMENTS

---

I would like to begin by expressing my deepest appreciation to all whom have contributed their precious time, knowledge and support towards the completion of my Doctoral thesis.

For the University of Technology, Sydney, I wish to sincerely thank my final year supervisors Dr Greg Heness and Dr Richard Wuhner for their guidance, encouragement and support throughout my research. In addition, I wish to thank my former supervisor Dr Wing Yui Yeung for providing me with the opportunity to conduct a challenging and engaging project. I also wish to thank fellow researchers Mr Tim Lucy and Mr Sam Humphries for their insightful comments and assistance from our weekly materials research meetings. Finally, I wish to mention Dr Norman Booth and Mr Greg Delsanto whom were gracious enough to provide their technical expertise and skills toward the completion of this degree. I would also like to extend a warm thanks to Prof. Zhang Di from Shanghai Jiao Tong University (SJTU) for allowing me the opportunity to conduct overseas research at the State Key Laboratory of Metal Matrix Composites. I would also like to thank Dr Qin JiNing for providing supervisory support. In addition, I wish to thank Dr Lu Weiji and Dr Ouyang Quibo whom provided the necessary materials for this research. I wish to express my thanks to Dr Tao Wei from the Australian Nuclear Science Technology Organisation (ANSTO) for support in mechanical testing and finite element analysis. I would also like to extend my thanks to Mr Darren Attard, Mr Graham Smith, Dr Massey De Los Reyes, Dr Mark Callaghan and Mr Tim Palmer for making my time at ANSTO memorable. I would also like to thank Mr Ken Moran and Mr Peter Davey from Moran Scientific for providing insight into the world of scanning electron microscopy with a few good burning jokes along the way.

Finally, I wish to express how grateful I am to my family and friends for their love, encouragement and support. And especially to my sister Mrs Lisa S. Lynch, who helped with much needed last minute editing!

I thank you all!

---

## TABLE OF CONTENTS

---

<b>ABSTRACT .....</b>	<b>I</b>
<b>CERTIFICATE OF AUTHORSHIP .....</b>	<b>II</b>
<b>ACKNOWLEDGEMENTS.....</b>	<b>III</b>
<b>TABLE OF CONTENTS.....</b>	<b>IV</b>
<b>LIST OF FIGURES .....</b>	<b>IX</b>
<b>LIST OF TABLES .....</b>	<b>XVI</b>
<b>LIST OF SYMBOLS .....</b>	<b>XVIII</b>
<b>CHAPTER ONE INTRODUCTION.....</b>	<b>1</b>
1.1 Background .....	2
1.2 Significance of this research .....	3
1.3 Research objectives .....	4
1.4 Statement of main findings .....	5
1.5 Publications arising from this research .....	6
1.6 Awards arising from this research.....	7
<b>CHAPTER TWO METAL MATRIX COMPOSITES.....</b>	<b>8</b>
2.1 Introduction .....	9
2.2 A brief history .....	10
2.3 The current market .....	11

---

2.4	Applications .....	13
2.4.1	Ground transport.....	13
2.4.2	Thermal management .....	14
2.4.3	Aerospace .....	16
2.5	Processing routes.....	17
2.5.1	Stir-cast process.....	18
2.5.2	Vacuum arc remelting process .....	19
2.6	Concluding remarks .....	20
<b>CHAPTER THREE MECHANICAL BEHAVIOUR.....</b>		<b>21</b>
3.1	Introduction .....	22
3.2	Strength .....	22
3.3	Fracture toughness .....	24
3.4	Failure and fracture mechanism .....	25
3.5	Concluding remarks .....	29
<b>CHAPTER FOUR FRACTURE TOUGHNESS TEST.....</b>		<b>30</b>
4.1	Introduction .....	31
4.2	Standard fracture toughness test.....	33
4.2.1	Single-edge bend test.....	33
4.2.2	Compact tension test .....	35
4.2.3	Chevron-notched short rod or bar tests .....	36
4.3	Non-standard fracture toughness test .....	41
4.3.1	Circumferential notch tension test.....	41
4.4	Concluding remarks .....	44
<b>CHAPTER FIVE THE SMALL PUNCH TEST.....</b>		<b>45</b>



---

5.1	Introduction .....	46
5.2	Defining the small punch test.....	47
5.3	Determination of the small punch elastic-plastic load, $P_y$ .....	53
5.4	Determination of the small punch energy, $E_{SP}$ .....	54
5.5	Determination of the small punch equivalent fracture strain, $\epsilon_{qF}$ .....	54
5.6	An analytical method for the determination of small punch maximum bend yield strength, $\sigma_y$ .....	56
5.7	An empirical method for the determination of plane-strain fracture toughness, $K_{Ic}$ and $J_{Ic}$ .....	60
5.8	Finite element methods for the small punch test.....	66
5.9	Neural networks for the small punch test.....	70
5.10	Concluding remarks .....	71
<b>CHAPTER SIX EXPERIMENTAL METHOD .....</b>		<b>72</b>
6.1	Introduction .....	73
6.2	Research materials .....	73
6.2.1	Aluminium materials .....	74
6.2.2	Titanium materials.....	75
6.3	Specimen orientation system.....	76
6.4	Metallographic procedure .....	77
6.5	Microstructural examination .....	79
6.6	Compositional analysis .....	80
6.6.1	Aluminium materials .....	80
6.6.2	Titanium materials.....	80

---

6.7	Quantitative x-ray mapping.....	81
6.8	Tensile testing .....	81
6.8.1	Flat tensile test specimens .....	81
6.9	Fracture toughness testing.....	85
6.9.1	Single-edge bend testing .....	85
6.9.2	Circumferential notch tension testing.....	87
6.9.3	Small punch testing .....	91
6.10	Finite elemental analysis of small punch test .....	94
6.11	Concluding remarks .....	95
<b>CHAPTER SEVEN RESULTS AND DISCUSSION.....</b>		<b>96</b>
7.1	Introduction .....	97
7.2	Aluminium results.....	97
7.2.1	The microstructure .....	97
7.2.2	The tensile test.....	103
7.2.3	The single-edge bend test .....	105
7.2.4	The circumferential notch tension test .....	112
7.2.5	Small punch test .....	122
7.2.6	Finite element analysis .....	129
7.3	Titanium results.....	132
7.3.1	The microstructure .....	132
7.3.2	The tensile test.....	137
7.3.3	The circumferential notch tension test .....	139
7.3.4	Small punch test .....	142
7.3.5	Finite element analysis .....	150
7.4	Concluding remarks .....	153
<b>CHAPTER EIGHT SMALL PUNCH TEST CORRELATIONS .....</b>		<b>154</b>

8.1	Introduction .....	155
8.2	Empirical correlations between the small punch and mechanical values .....	159
8.2.1	Correlating yield strength, $\sigma_{YS}$ , and small punch elastic-plastic load, $P_y$ .....	159
8.2.2	Correlating plane-strain fracture toughness, $J_{Ic}$ and small punch equivalent fracture strain, $\epsilon_{qF}$ .....	166
8.2.3	Correlating plane-strain fracture toughness, $J_{Ic}$ , with the small punch energy, $E_{SP}$	170
8.3	An analytical approach for the determination of the small punch maximum bend strength, $\sigma_y$ .....	174
8.4	A literature survey of the plane-strain fracture toughness, $J_{Ic}$ , and small punch equivalent fracture strain, $\epsilon_{qF}$ .....	181
8.5	A potential small punch analytical solution to derive the plane-strain fracture toughness, $J_{Ic}$ .....	184
8.6	Concluding remarks .....	185
<b>CHAPTER NINE CONCLUSIONS .....</b>		<b>187</b>
9.1	Conclusions regarding the small punch test.....	188
<b>CHAPTER TEN FUTURE WORK.....</b>		<b>191</b>
<b>REFERENCES.....</b>		<b>193</b>
<b>APPENDIX I .....</b>		<b>206</b>

---

## LIST OF FIGURES

---

Figure 1–1. Article publication history for the small punch test, data from SciFinder.....	2
Figure 2–1. Metal matrix composites for the transport industry (a) engine block (b) piston lining and (c) piston head [34]. .....	14
Figure 2–2. Materials for thermal management. Optimum materials for electronic packaging and thermal management are located within the shaded band [34].....	15
Figure 2–3. Metal matrix composites for thermal management and electronic packaging, MMCC Inc. [40]. .....	16
Figure 2–4. Metal matrix composites for the aerospace (a) F-16 fighter aircraft ventral fins (b) F-16 fighter fuselage doors and (c) Hubble space telescope high gain antennae wave guide boom [28, 34].....	17
Figure 2–5. The stir-cast processing route for metal matrix composites [28]. .....	19
Figure 2–6. Non-consumable vacuum arc remelting furnace (a) diagram and (b) furnace employed at the State Key Laboratory of Metal Matrix Composites. ....	20
Figure 3–1. Tensile behaviour for Al-Cu-Mg 2080/SiC <sub>p</sub> -T8 metal matrix composites with increasing reinforcement content [28, 50]. .....	23
Figure 3–2. The fracture toughness for several particulate reinforced metal matrix composite with increasing reinforcement content [28, 63].....	24
Figure 4–1. The effect of specimen thickness on fracture toughness [76].....	31
Figure 4–2. American Society for Testing and Materials single-edge bend test specimen [77].....	33
Figure 4–3. American Society for Testing and Materials compact tension test specimen [77].....	36
Figure 4–4. American Society for Testing and Materials chevron-notched (a) short rod and (b) short bar specimens [78].....	37
Figure 4–5. A comparison of the (a) compact tension and (b) chevron-notched short rod specimen [83]. .....	40
Figure 4–6. The circumferential notch tensile test configuration [95].....	41
Figure 4–7. A comparison of the circumferential notch tension and the standard compact tension specimens test size [95].....	43
Figure 5–1. The Massachusetts Institute of Technology small punch test [98].....	46
Figure 5–2. A schematic representation of the small punch test configuration. ....	48

Figure 5–3. Small punch disk-shaped specimens cut from a cylindrical sample.....	50
Figure 5–4. Small punch test load-displacement curve [149].....	52
Figure 5–5. The <i>offset</i> method and 2 <i>tangent</i> method for the determination of elastic-plastic load, $P_y$ [152].....	53
Figure 5–6. A flat circular plate with constant thickness [156]. Where $P_y$ is the small punch elastic-plastic load, $r_o$ is the radius of the spherical punch and $R_l$ is the radius of the lower die bore.....	56
Figure 5–7. Method for the determination of the elastic deformation energy, EDE and the elastic displacement, $D_e$ [152].....	60
Figure 5–8. The theoretical plane strain fracture toughness $J_{Ic}$ and equivalent fracture strain relationship proposed by Bayoumi and Bassim [26]. ....	61
Figure 5–9. Infinite sharp notched plate-shaped small punch test subjected to uniform bending. Where $M_o$ is the bending moment applied around the boundaries of an infinite plate.....	63
Figure 5–10. Procedure for estimating the fracture toughness by evaluating the local strain energy density from small punch test load-displacement curve [148].....	68
Figure 5–11. Parameters that govern each region of the small punch test load-displacement curve for structural steels [149]. ....	69
Figure 5–12. Neural network procedure to determine small punch test mechanical parameters [139].....	71
Figure 6–1. The as-received materials consist of (a) 7A04-T6, (b) 7A04/SiC/7.5p-T6, (c) 7A04/SiC/10p-T6, (d) TC4, (e) TC4/TiB, TiC/2.5w, 2.5p and (f) TC4/TiB, TiC/5w, 5p.....	73
Figure 6–2. The as-machined mechanical test specimen orientation for the (a) SPT specimen, (b) tensile test specimen and (c) circumferential notch tension test specimen. Where L is the direction of the principle grain flow, T is the direction of least deformation and S is the third orthogonal direction. ....	76
Figure 6–3. the formation of spot dimples or comet-like dimple on the surface of TC4 alloy after 1 $\mu$ m diamond polishing. ....	78
Figure 6–4. Australian Standard tensile specimen [153] (a) specimen configuration and (b) machined specimen. Where a represents the thickness, $L_c$ is the parallel length, b is the parallel lengths and $L_t$ is the total length of the test piece. ....	82

Figure 6–5. The tensile test setup with a flat tensile specimen clamped between two pairs of tension wedge grips. An extensometer is attached to the tensile specimen for strain measurement. The load capacity of the wedge grips are 100kN.....	84
Figure 6–6. (a) single-edge bend fracture toughness test specimen and (b) straight-through notch. ....	85
Figure 6–7. The high speed fatigue precracker. ....	86
Figure 6–8. The circumferential notched tension test (a) specimen configuration and (b) machined specimen. ....	87
Figure 6–9. Rotational-bend fatigue machine, to induce a precrack in the circumferential notch tension test specimen.....	88
Figure 6–10. Circumferential notch tension test (a) specimen held by split-collet grips. ....	90
Figure 6–11. The small punch test specimen configuration. ....	91
Figure 6–12. The small punch test configuration (a) schematic diagram (b) experimental setup at the University of Technology, Sydney. ....	93
Figure 6–13. The finite element model of the small punch test configuration. ....	94
Figure 7–1. Backscatter electron micrographs for the as-received (a, b, c) 7A04-T6 aluminium alloy, (d, e, f) 7A04/SiC/7.5p-T6 aluminium MMC and (g, h, i) 7A04/SiC/10p-T6 aluminium MMC.....	98
Figure 7–2. Backscatter electron micrographs for the as-received (a, b, c) 7A04-T6 aluminium alloy, (d, e, f) 7A04/SiC/7.5p-T6 aluminium MMC and (g, h, i) 7A04/SiC/10p-T6 aluminium MMC.....	99
Figure 7–3. Pseudo colour quantitative x-ray mapping for the as-received (a) 7A04-T6 aluminium alloy, (b) 7A04/SiC/7.5-T6 aluminium MMC and (c) 7A04/SiC/10-T6 aluminium MMC. The mapping parameters included 6000cps, 20kV and 512x512 pixels resolution. ....	102
Figure 7–4. Engineering stress-strain behaviour for 7A04-T6 aluminium alloy, 7A04/SiC/7.5p-T6 aluminium MMCs and 7A04/SiC/10p-T6 aluminium MMCs.....	103
Figure 7–5. Single-edge bend test specimen in a three point bending configuration. ..	105
Figure 7–6. Fracture toughness load-displacement curve for 7A04-T6 aluminium alloy. ....	108
Figure 7–7. Fracture toughness load-displacement curve for 7A04-T6 aluminium alloy. ....	108

Figure 7–8. Fracture toughness load-displacement curve for 7A04-T6 aluminium alloy. ....	109
Figure 7–9. Secondary electron image of the aluminium MMCs fracture surface at the crack tip. The shallow crack length is approximately 200µm as indicated in the micrograph. ....	110
Figure 7–10. Backscatter secondary electron image of the aluminium MMCs fracture surface. ....	110
Figure 7–11. Circumferential notch tension precrack fracture surface for 7A04-T6 alloys. The top and bottom fractographs for each column are the matching fracture halves for each specimen. The letters A, B and C are used in this section to designate the test specimens. ....	112
Figure 7–12. Circumferential notch tension load curves for the 7A04-T6 aluminium materials. The letters A, B and C are used in this section to designate the test specimens. ....	113
Figure 7–13. Circumferential notch tension precrack fracture surface for the 7A04/SiC/7.5p-T6 aluminium materials. The top and bottom fractographs for each column are the matching fracture halves for each specimen. The letters A, B and C are used in this section to designate the test specimens. ....	115
Figure 7–14. Side view of the circumferential notch tension precrack fracture surface for the 7A04/SiC/7.5p-T6 aluminium materials. The letters A, B and C are used in this section to designate the test specimens. ....	115
Figure 7–15. Circumferential notch tension load curves for the 7A04/SiC/7.5p-T6 aluminium materials. The letters A, B and C are used in this section to designate the test specimens. ....	116
Figure 7–16. Circumferential notch tension precrack fracture surface for 7A04 /SiC/10p-T6 MMCs. The top and bottom fractographs for each column are the matching fracture halves for each specimen. The letters A, B and C are used in this section to designate the test specimens. ....	117
Figure 7–17. Side view of the circumferential notch tension precrack fracture surface for the 7A04/SiC/10p-T6 aluminium materials. The letters A, B and C are used in this section to designate the test specimens. ....	117

Figure 7–18. Circumferential notch tension load curves for 7A04/SiC/10p-T6 aluminium materials. The letters A, B and C are used in this section to designate the test specimens. ....	118
Figure 7–19. The 7A04-T6 aluminium alloy fracture surface exhibiting a common flaw. ....	121
Figure 7–20. Typical small punch test load-displacement curves for 7A04-T6 aluminium alloy. ....	123
Figure 7–21. Typical small punch test load-displacement curves for 7A04-T6/SiC/7.5p-T6 aluminium MMC. ....	123
Figure 7–22. Typical small punch test load-displacement curves for 7A04-T6/SiC/10p-T6 aluminium MMC. ....	124
Figure 7–23. Averaged small punch test load-displacement curves for 7A04-T6 aluminium alloy, 7A04/SiC/7.5p-T6 aluminium MMC and 7A04/SiC/10p-T6 aluminium MMC. The dots indicate the observed load at crack initiation. ....	124
Figure 7–24. Micrographs illustrating the small punch test crack profile for (a) 7A04-T6, (b) 7A04/SiC/7.5p-T6 and (c) 7A04/SiC/10p-T6 aluminium materials. ....	127
Figure 7–25. Backscatter electron micrograph illustrating the cross-section of the small punch test crack profile for (a) 7A04-T6, (b) 7A04/SiC/7.5p-T6 and (c) 7A04/SiC/10p-T6 aluminium materials. ....	128
Figure 7–26. Finite element prediction of the small punch load-displacement curve for aluminium materials. ....	129
Figure 7–27. Crack initiation and propagation behaviour for 7A04/SiC/7.5p-T6 aluminium MMC with increasing loads. ....	130
Figure 7–28. Crack initiation and propagation behaviour for 7A04/SiC/10p-T6 aluminium MMC with increasing loads. ....	130
Figure 7–29. Finite element prediction of the small punch load-displacement curve for aluminium materials up to 200N. ....	131
Figure 7–30. Backscatter secondary electron micrographs for the as-received (a, b, c) TC4 titanium alloy, (d, e, f) TC4/TiB, TiC/2.5w, 2.5p titanium MMC and (g, h, i) TC4/TiB, TiC/5w, 5p titanium MMC. ....	133
Figure 7–31. Backscatter secondary electron micrographs for the as-received (a, b, c) TC4 titanium alloy, (d, e, f) TC4/TiB, TiC/2.5w, 2.5p titanium MMC and (g, h, i) TC4/TiB, TiC/5w, 5p titanium MMC. ....	134



Figure 7–32. Pseudo coloured Quantitative x-ray mapping for as-received (a) TC4 titanium alloy (b) TC4/TiB, TiC/2.5w, 2.5p titanium MMC and (c) TC4/TiB, TiC/5w, 5p titanium MMC. The image size is set to 512x512 pixels, 16kV acceleration voltage. All Quantitative x-ray mapping is weighted averaged.....	136
Figure 7–33. Engineering stress-strain behaviour for TC4 titanium alloy, TC4/TiB, TiC/2.5w, 2.5p titanium MMC and TC4/TiB, TiC/5w, 5p titanium MMC.....	137
Figure 7–34. Circumferential notch tension test fracture surface for the (a) TC4, (b) TC4/TiB, TiC/2.5w, 2.5p and (c) TC4/TiB, TiC/5w, 5p. The top and bottom fractographs for each column are the matching fracture halves for each specimen. ....	140
Figure 7–35. Circumferential notch tension load curves for titanium materials.....	141
Figure 7–36. Typical small punch test load-displacement curves for TC4 titanium alloy. ....	142
Figure 7–37. Typical small punch test load-displacement curves for TC4/TiB, TiC/2.5w, 2.5p titanium MMC. ....	143
Figure 7–38. Typical small punch test load-displacement curves for TC4/TiB, TiC/5w, 5p titanium MMC.....	143
Figure 7–39. Averaged small punch test load-displacement curves for TC4 titanium alloy, TC4/TiB, TiC/2.5W, 2.5p titanium MMC and TC4/TiB, TiC/5W, 5p titanium MMC. The dots indicate the observed load at crack initiation. ....	144
Figure 7–40. Shear punch load-displacement curve for various materials including MMCs [202, 203].....	145
Figure 7–41. Fractographs showing the cracking profile of (a) TC4 titanium alloy, (b) TC4/TiB, TiC/2.5w, 2.5p titanium MMC, (c) TC4/TiB, TiC/5w, 5p titanium MMC at increasing magnifications.....	148
Figure 7–42. Side view of the small punch test crack profile for (a) TC4 titanium alloy, (b) TC4/TiB, TiC/2.5w, 2.5p titanium MMC and (c) TC4/TiB, TiC/5w, 5p titanium MMC.....	149
Figure 7–43. Finite element prediction of the small punch load-displacement curves for titanium materials.....	150
Figure 7–44. Crack initiation and propagation behaviour for TC4/TiB, TiC/2.5w, 2.5p titanium MMC with increasing loads.....	151
Figure 7–45. Crack initiation and propagation behaviour for TC4/TiB, TiC/2.w, 2.5p titanium MMC with increasing loads.....	151

Figure 7–46. Finite element prediction of the small punch load-displacement curve for titanium materials up to 300N.....	152
Figure 8–1. A qualitative comparison of the methods for deriving small punch elastic-plastic load, $P_y$ .....	159
Figure 8–2. Correlation of the yield strength, $\sigma_{YS}$ , and the small punch elastic-plastic load, $P_y$ , for aluminium materials.....	162
Figure 8–3. Correlation of the yield strength, $\sigma_{YS}$ , and the small punch elastic-plastic load, $P_y$ , for titanium materials.....	163
Figure 8–4. Correlation of the yield strength, $\sigma_{YS}$ , and the small punch elastic-plastic load, $P_y$ , for both aluminium and titanium materials. ....	164
Figure 8–5. A correlation of the plane-strain fracture toughness, $J_{Ic}$ , and equivalent fracture strain, $\epsilon_{qF}$ , for aluminium materials. ....	167
Figure 8–6. A correlation of the plane-strain fracture toughness, $J_{Ic}$ , and equivalent fracture strain, $\epsilon_{qF}$ , for titanium materials. ....	168
Figure 8–7. A correlation of the plane-strain fracture toughness, $J_{Ic}$ , and equivalent fracture strain, $\epsilon_{qF}$ , for both aluminium and titanium materials. ....	168
Figure 8–8. A correlation of normalised plane-strain fracture toughness/yield strength, $K_{Ic}/\sigma_{YS}$ , and equivalent fracture strain, $\epsilon_{qF}$ , relationship for both aluminium and titanium materials. ....	169
Figure 8–9. A qualitative comparison of the methods for deriving small punch energy, $E_{SP}$ . Where (a) is the energy up to crack initiation, (b) is the total small punch energy and (c) is the energy after crack initiation.....	170
Figure 8–10. A correlation of the plane-strain fracture toughness, $J_{Ic}$ , and total small punch energy, $E_{SP}$ .....	172
Figure 8–11. A geometric method for determining the small punch equivalent contact radius, $r'$ .....	174
Figure 8–12. Analytical solutions for solving the small punch maximum bend strength, $\sigma_y$ . ....	177
Figure 8–13. A correlation of the tensile yield strength, $\sigma_{YS}$ , plotted against small punch maximum bend strength, $\sigma_y$ . ....	179
Figure 8–14. A global overview of the relationship between plane-strain fracture toughness, $J_{Ic}$ , and the .....	182

---

## LIST OF TABLES

---

Table 2-1. Classification system for reinforcements.....	10
Table 2-2. The current market and applications for metal matrix composites.....	12
Table 2-3. Processing routes for metal matrix composites. ....	18
Table 4-1. Stress intensity factors relevant to the chevron-notched short rod and bar fracture toughness test. ....	38
Table 5-1. Small punch test specimen and die configurations.....	49
Table 5-2. Reported yield strength correlation coefficients for the small punch test. ....	58
Table 6-1. The nomenclature for the aluminium research material. ....	74
Table 6-2. The nomenclature for the titanium research materials. ....	75
Table 6-3. The chemical composition (wt.%) for the 7A04-T6 base alloy.....	80
Table 6-4. The chemical composition (wt.%) for the TC4 base alloy. ....	80
Table 6-5. Accutom-50 cut-off saw parameters for aluminium based materials. ....	91
Table 7-1. The particle size and volume percent of SiC <sub>p</sub> for aluminium metal matrix composites.....	101
Table 7-2. Tensile mechanical properties for 7A04-T6 aluminium alloy, 7A04/SiC/7.5p-T6 aluminium MMC and 7A04/SiC/10p-T6 aluminium MMC. ....	104
Table 7-3. The 7A04-T6 aluminium base alloy single-edge bend loads, validity requirements and fracture toughness values. The 0.2% off-set yield strength, $\sigma_{YS}$ , for the 7A04-T6 aluminium base alloy is 462MPa. ....	107
Table 7-4. Circumferential notch tension plane-strain fracture toughness, $K_{Ic}$ , values for the 7A04-T6 aluminium materials. The letters A, B and C are used in this section to designate the test specimens.....	114
Table 7-5. Circumferential notch tension plane-strain fracture toughness, $K_{Ic}$ values for the 7A04/SiC/7.5p-T6 aluminium materials. The letters A, B and C are used in this section to designate the test specimens. ....	116
Table 7-6. Circumferential notch tension plane-strain fracture toughness, $K_{Ic}$ values for the 7A04/SiC/10p-T6 aluminium materials. The letters A, B and C are used in this section to designate the test specimens. ....	118
Table 7-7. Summary of the valid circumferential notched tension test fracture toughness specimens. ....	120
Table 7-8. Circumferential notched tension fracture toughness results. ....	120

---

Table 7-9. Compositional analysis of 7A04-T6 aluminium alloy.....	121
Table 7-10. Small punch test properties for the as-received aluminium based materials. .....	125
Table 7-11. The statistical difference between two small punch energy, $E_{SP}$ , 7A04-T6 aluminium MMCs. ....	126
Table 7-12. The particle size and volume percent for titanium MMCS. ....	135
Table 7-13. Tensile properties for TC4 titanium alloy, TC4/TiB, TiC/2.5w, 2.5p TC4/TiB, TiC/5w, 5p MMC. ....	138
Table 7-14. Circumferential notch tension plane-strain fracture toughness, $K_{Ic}$ values for the titanium materials. ....	141
Table 7-15. Small punch test properties for the as-received titanium materials.....	146
Table 7-16. The statistical difference between two small punch energy, $E_{SP}$ , TC4 titanium MMCs. ....	147
Table 8-1. Summary of the small punch test $P_y$ , $\epsilon_{qF}$ and $E_{SP}$ values for aluminium and titanium materials.....	156
Table 8-2. Summary of conventional mechanical properties $\sigma_{YS}$ , $K_{Ic}$ and $J_{Ic}$ , values for aluminium and titanium materials.....	157
Table 8-3. Comparison of small punch and conventional mechanical properties. ....	158
Table 8-4. Correlation coefficients, $\alpha$ , for the aluminium and titanium materials.....	164
Table 8-5. Calculated small punch energies. ....	171

---

## LIST OF SYMBOLS

---

Symbol	Unit	Description
$r_o$	mm	Small punch ball radius
$R_u$	mm	Small punch hole radius of the upper die
$R_l$	mm	Small punch hole radius of the lower die
$r^*$	mm	Small punch chamfer edge
$d_o$	mm	Small punch specimen diameter
$t_o$	mm	Small punch specimen thickness
$t_f$	mm	Small punch minimum thickness at fracture
$r'$	mm	Small punch equivalent contact radius
$\delta^*$	mm	Small punch displacement at fracture
$\delta_y$	mm	Small punch elastic-plastic displacement
$P_y$	N	Small punch elastic-plastic load
$P_i$	N	Small punch load at crack initiation
$P_{max}$	N	Small punch maximum load
$E_{SP}$	J	Small punch fracture energy
$\epsilon_{qF}$	-	Small punch equivalent fracture strain
$\sigma_y$	MPa	Small punch maximum bend strength
$\alpha$	-	Small punch correlation coefficient
$\sigma_{YS}$	MPa	Yield strength
$\sigma_{UTS}$	MPa	Ultimate tensile strength
$E$	GPa	Elastic modulus
$\nu$	-	Poisson's ratio
$J_{1c}$	$\text{kJ/m}^2$	Ductile plane-strain fracture toughness
$K_{1c}$	$\text{MPa}\sqrt{\text{m}}$	Brittle plane-strain fracture toughness
$n$	-	Strain hardening exponent